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A LOW-LOAD THREE-COMPONENT FORCE BALANCE FOR MEASUREMENTS IN A LOW-DENSITY WIND TUNNEL

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NOTICES

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FOREWORD

The authors are grateful to the several persons who have made helpful suggestions throughout this work. Special acknowledgment is due Mr. A. B. Bailey, Mr. J. F. Roy, Mr. J. C. Potter, Mr. R. P. Van Hook and Mr. D. E. Boylan.

ABSTRACT

This paper describes a three-component force balance which has been developed for measurement of lift, drag, and pitching moment acting on models in a low-density, hypervelocity wind tunnel. Although designed for a particular wind tunnel, the general arrangement and the principles involved should be applicable to similar situations.

The balance is of the external type operating on the nulling principle. Nulling of each component is accomplished automatically through the use of closed loop control systems. Calibration data and sample wind tunnel measurements are presented which demonstrate that the balance is suitable for the intended application.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

John R. Cureton
Captain, USAF
Gas Dynamics Division
DCS/Research

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Colonel, USAF
DCS/Test

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1.0 INTRODUCTION

Noticeably lacking in the reported literature on gas dynamics is a significant amount of wind tunnel data pertaining to aerodynamic forces acting on bodies in high-speed, rarefied flow fields. This is partially due to a lack of sufficiently sensitive force-measuring balances capable of obtaining data in the typically small, low-density wind tunnel of today, wherein limited model size combines with the rarefied flow to result in extremely small forces. To the authors' knowledge, little has been done to correct this deficiency beyond the development of simple, single-component, drag balances.

The purpose of this report is to document the development of a three-component balance which is capable of resolving lift, drag, and pitching moment in the relatively typical low-density wind tunnel (Gas Dynamic Wind Tunnel, Hypersonic (L))(Ref. 1), at the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC). Briefly, this tunnel is a continuous type, arc-heated, ejector-pumped, hypersonic system. Based on typical tunnel flow conditions, initial performance requirements established for the balance were as follows:

	Maximum Load (lbf or in. -lbf)	Accuracy (lbf or in. -lbf)
Drag	2×10^{-2}	$\pm 2 \times 10^{-4}$
Lift	$\pm 2 \times 10^{-3}$	$\pm 4 \times 10^{-5}$
Moment*	$\pm 4 \times 10^{-3}$	$\pm 4 \times 10^{-5}$

Additional requirements originally set forth having a governing influence on the balance design were:

1. The size obstruction allowable in the flow field is unusually restricted because of small tunnel size, i. e., models are roughly 0.5 in. in maximum diameter.
2. The balance must be insensitive to the near vacuum environment on the order of 10 microns Hg and to heat transfer from the relatively high-enthalpy flow fields wherein total temperatures are up to 7200°R.

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*For the purpose of defining pitching-moment range and accuracy, the moment center is defined as a point on the end of the model sting at its centerline.

Manuscript received December 1964.

2.0 DESCRIPTION OF THE BALANCE

The balance is of the external type and is composed of one drag and two lift components, pitching moment being determined from the latter two. All components operate on the nulling principle. The mechanical arrangement of the balance can best be explained by reference to Fig. 1. Note first that the model supporting sting is rigidly attached to a yoke which is supported by the two lift components through vertical flexures. In turn, each lift component is supported through the use of two sets of cross flexures and is braced in the vertical position by a horizontal stiffened flexure. Both the cross flexures and stiffened flexures are made of stainless steel shim stock of sufficient width to give lateral stability. A static weight is used to counterbalance the lift component, yoke, sting, test model, etc. In order to reduce the mass of the system, all dynamic components were made of the lighter metals, aluminum and magnesium.

Nulling and measurement of the force acting through each lift component is accomplished automatically through a closed loop control system as shown schematically in Fig. 2a. Any error in the vertical position of a particular component is sensed by a differential transformer which transmits this information to a servoamplifier. This amplifier in turn sends a current through the driving coil of a magnet assembly which, through a series of flexures, applies the necessary force through the component to maintain a null position. Finally, the magnitude of the current is recorded on a strip chart and is a measure of the restoring force acting through the component. One obtains the output for an applied load simply by subtracting the reading before or after the load is applied from the reading obtained during load. Depending on the weight of the test model attached to the sting, it is, of course, usually necessary to position the counterweight so that the required driving current for nulling the balance will be within range of the servo.

Drag is measured by applying restoring forces to each side of the yoke at the points shown in Fig. 1. The drag measurement is obtained by summing these two forces. This was done as a matter of convenience and is not intended as another component in the balance. However, it is conceivable that with minor changes in the flexures connecting the drag servos to the yoke, it would be possible to measure yawing moment.

The drag nulling and measurement systems are similar to those for lift, the main difference being in the linkages and the fact that Consolidated Electrodynamics Corp. Type 1-124 servoamplifiers were used in lieu of their type 1-126 (see Fig. 2b). Also, it may be noted that no

dashpots were required for damping as was the case with the lift components.

A photograph of the balance is shown in Fig. 3. This is included primarily to show the aerodynamic shielding of the components in or near the flow field. The horizontal shield for the rear of the yoke assembly and the top of the balance housing are water cooled. Not shown in the photograph are the side plates for the balance housing.

3.0 STATIC CALIBRATION

The technique used for static calibration of the balance is illustrated by Fig. 4. Briefly, drag loading was accomplished by use of standard weights suspended over a pulley, while lift and moment loading was accomplished by suspending standard weights from the model supporting structure at eight different load stations.

Calibration of the drag component in counts output versus applied load is shown in Fig. 5. Data points obtained with the balance operating both at atmospheric pressure and near vacuum are shown. Also, several points were repeated with artificial lift load applied. No interaction of lift on drag measurements could be detected. Linearity is seen to be very satisfactory with the best straight line through the data yielding a calibration constant of 1.488×10^{-4} lb_f/count. Since none of the calibration points deviate from this straight line by more than a count, it is concluded that the accuracy of the drag component is within the bounds of the original design requirement of $\pm 2 \times 10^{-4}$ lb_f throughout the required range.

For lift components L_1 and L_2, the counts output versus applied lift load at each of the eight load stations (see Fig. 4) is shown in Fig. 6. Attention is called to the fact that the data include points obtained under vacuum as well as at atmospheric pressure. Also, points are included where an artificial drag load was applied continuously.* As desired, all the data for each station form a straight line for both L_1 and L_2. By next reading the slope of these straight lines, the output counts per unit load were plotted versus load station location as shown in Fig. 7. Again,

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*The reader should not conclude from these points that there is no interaction of drag on L_1 and L_2. As a matter of fact there is a small scale shift which will be discussed later. These data are included to show that there is no change in sensitivity when drag load is applied.

straight lines fit the plotted points. Finally, calibration constants for L_1 and L_2 were both determined to be 3.33×10^{-5} lb_f/count.

The calibration data were next analyzed to determine extent of error in lift and moment measurements resulting from use of this calibration factor. Applied lift load should equal, within specified tolerances, the sum of L_1 and L_2 measurements. Similarly, about the balance moment center, the moment introduced by the applied lift load, or the product of the applied lift load and its moment arm, should be equal to the summation of restraining moments obtained from measured L_1 and L_2 and respective moment arms (see Fig. 4). The measurement errors found by comparison in this manner are shown in Figs. 8 and 9 for lift and moment, respectively. Again, it is noted that the balance performs within original design requirements throughout the required load range.

As stated previously, the addition of drag loads results in a zero or scale shift in L_1 and L_2 output. The magnitude of this shift versus the applied drag load is shown plotted in Fig. 10. Fortunately, the shift is linear and of small magnitude.

4.0 SAMPLE WIND TUNNEL FORCE MEASUREMENTS

As a preliminary to making force measurements on lifting bodies, the interaction of drag on L_1 and L_2 was again calibrated, with the drag load being applied by mounting spheres of assorted sizes on the balance in the actual wind tunnel flow. Since spheres should cause zero lift and moment, this is a satisfactory method of accounting for any slight misalignment of the balance and the flow field. The result of this calibration is shown in Fig. 10. As was the case with the static calibration, the interaction is linear and of small magnitude. This latter calibration with spheres was used to correct for interactions during subsequent wind tunnel measurements.

For the purpose of obtaining sample lift, drag, and pitching-moment data, a blunted 10-deg cone with a 0.5-in. base diameter was chosen as the test model. This particular model was chosen because drag data had been obtained for it using a single-component balance in the same flow field being used to test the present balance (see Ref. 2). The flow conditions used for the tests were as follows:

Working Gas	Nitrogen
Total Temperature	3960°R
Total Pressure	20 psia
Mach Number	9.9
Unit Reynolds Number	750/in.

In making wind tunnel measurements, the procedure was to first obtain zero readings on all components with no flow, but with the tunnel under vacuum. Then flow was established and readings were obtained with flow over the test model. Finally, flow was stopped and zero readings again obtained. The entire procedure consumed less than 45 sec on the average, allowing little time for heat transfer to affect the balance mechanism.

Resulting measurements on the blunted cone are shown in Fig. 11. Note that the drag data fall within the band of scatter of the previous data obtained with the single-component balance. Unfortunately, there are no other data for equally low-density flow conditions with which to compare the lift and pitching-moment measurements. As would be expected, however, the results do lie between the values obtained from the extreme cases of free-molecular and Newtonian theories.

Since the rear of the sting shield (see Fig. 3) is exposed to a pressure not necessarily equal to the natural model base pressure, the question may arise regarding an influence on the balance measurements. Because of the hypersonic flow condition, it can be shown by the ratio of impact pressure to the pressures involved at the base that there should be a negligible influence. Moreover, the present drag measurements compare very well with the single-component balance wherein the same problem did not exist. As a further check on base pressure effects on the present balance, the pressure to which the rear of the sting shield was exposed was varied from approximately 60 to 160 microns Hg. Also, the spacing between the rear of the test model and the end of the sting shield was varied from approximately 0.05 to 0.5 in. No significant change in the balance measurements was detected in either case.

5.0 CONCLUDING REMARKS

From the standpoint of producing minimal obstruction in the flow field and also from the standpoint of minimizing effects of heat transfer, the choice of an external balance design has been shown to be satisfactory. Automatic nulling and force measurement through the use of closed loop control systems on each of the three components proved to be adequate for obtaining the required sensitivity. It should be noted that the balance met the original design specifications, i.e., measurement of lift within $\pm 4 \times 10^{-5}$ lb_f, drag within $\pm 2 \times 10^{-4}$ lb_f, and moment within 4×10^{-5} in.-lb_f.

As was shown in the data presented, the operating environment did not have any adverse effects on balance performance. The bench calibration is precisely the same as that under tunnel conditions. During

the usual test interval, approximately 45 sec, there is no significant zero shift attributable to varying model temperature.

The balance, although designed for a specific tunnel, could be easily modified to operate in tunnels of different configurations. The load range of the balance is also quite flexible and can be increased or possibly decreased by use of different driving coils. It is also feasible to modify the balance so as to provide a five-component balance--lift, drag, side force, pitching moment, and yawing moment. This could be accomplished by modifying the two drag components to read yawing moment as well as drag force and adding a component to sense side force.

REFERENCES

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2. Boylan, David E. and Sims, William H. "Experimental Determination of Aerodynamic Drag on a Blunted 10-deg Cone at Angles of Attack in Hypersonic, Rarefied Flow." AEDC-TDR-64-60 (AD 435860), April 1964.

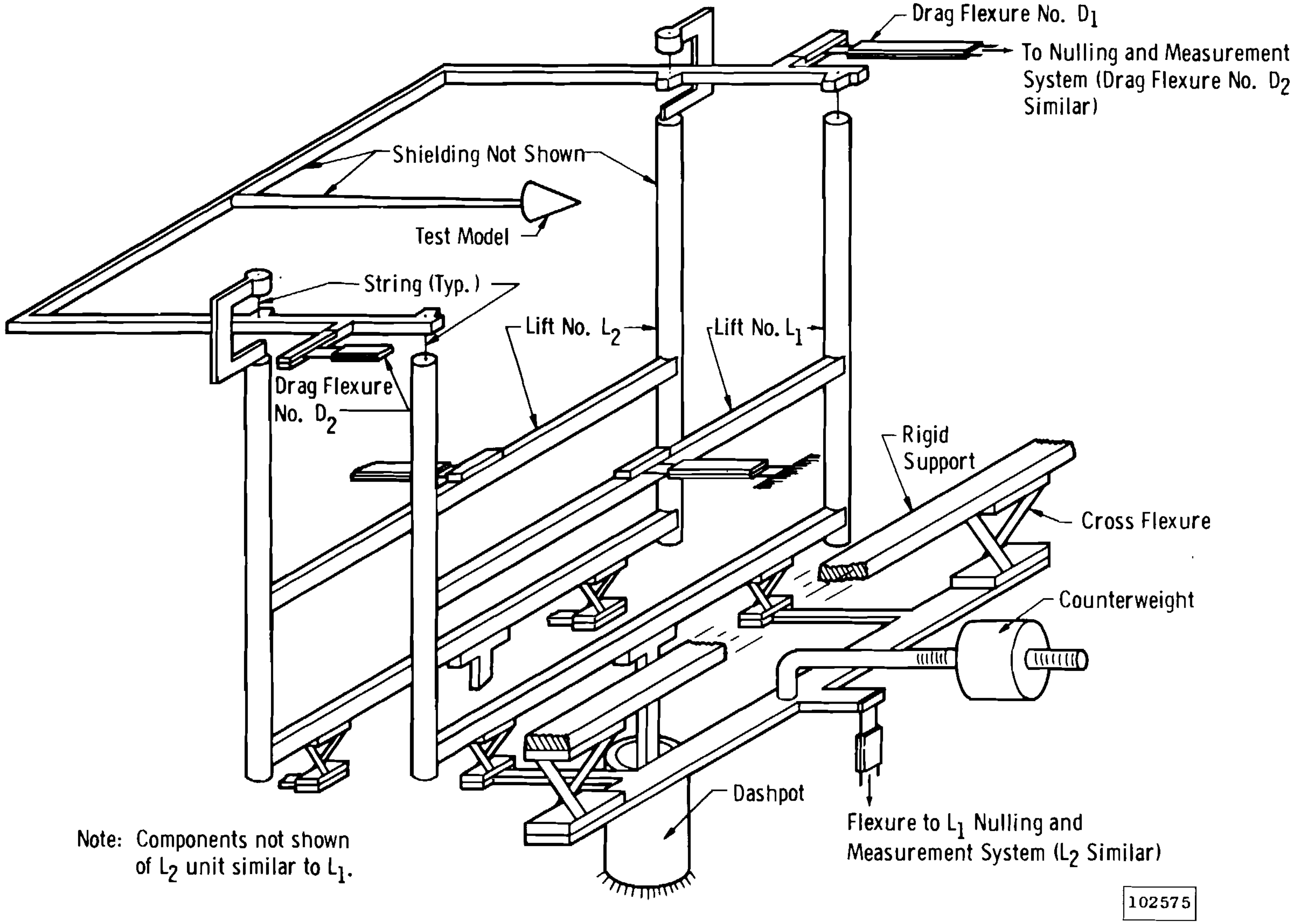
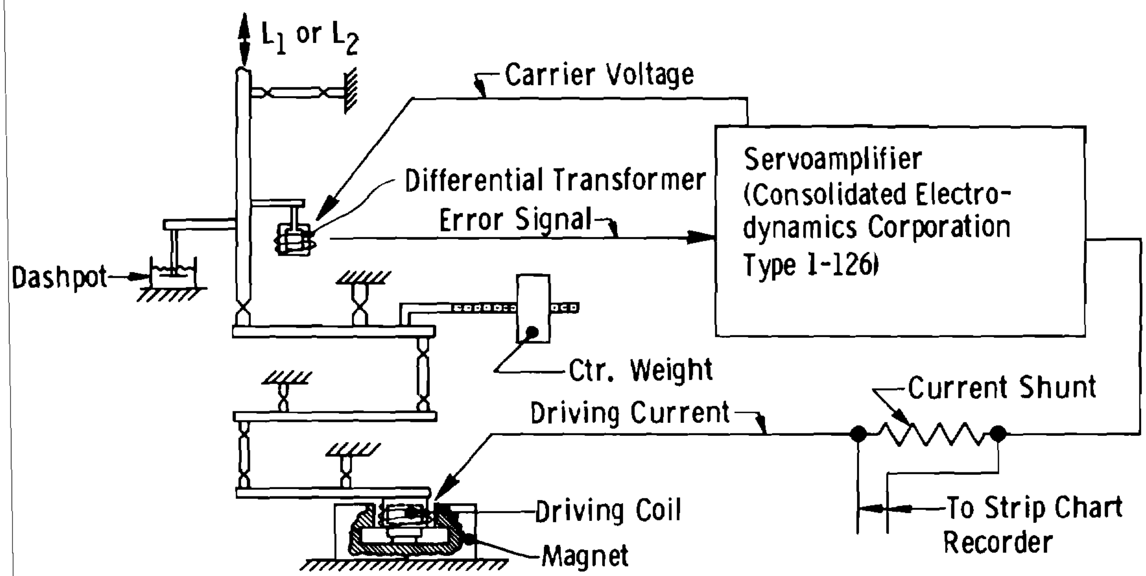
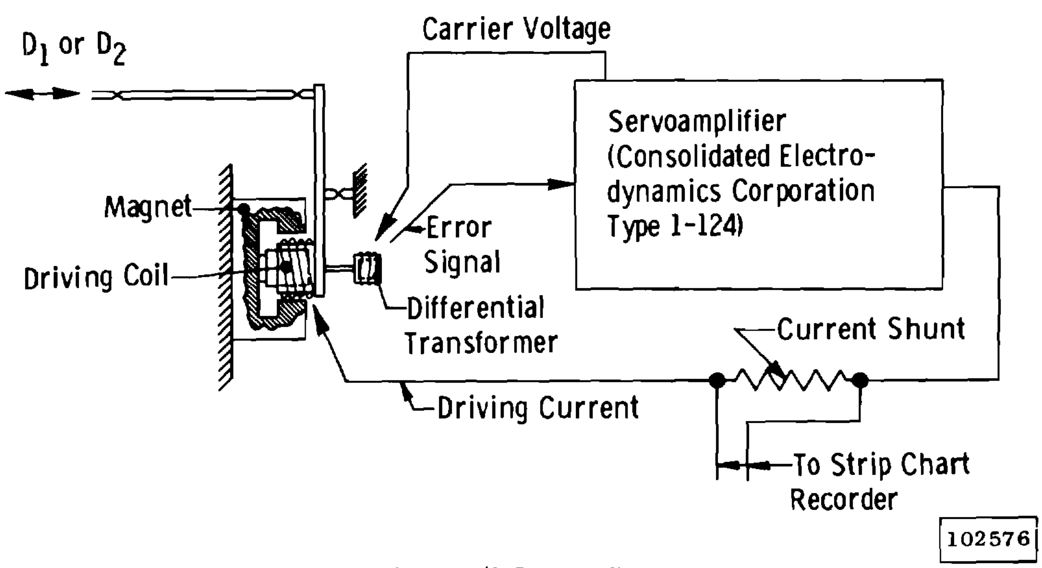


Fig. 1 Mechanical Arrangement of Balance



a. Lift System (2 Required)



b. Drag System (2 Required)

Fig. 2 Schematic of Nulling and Measurement Systems

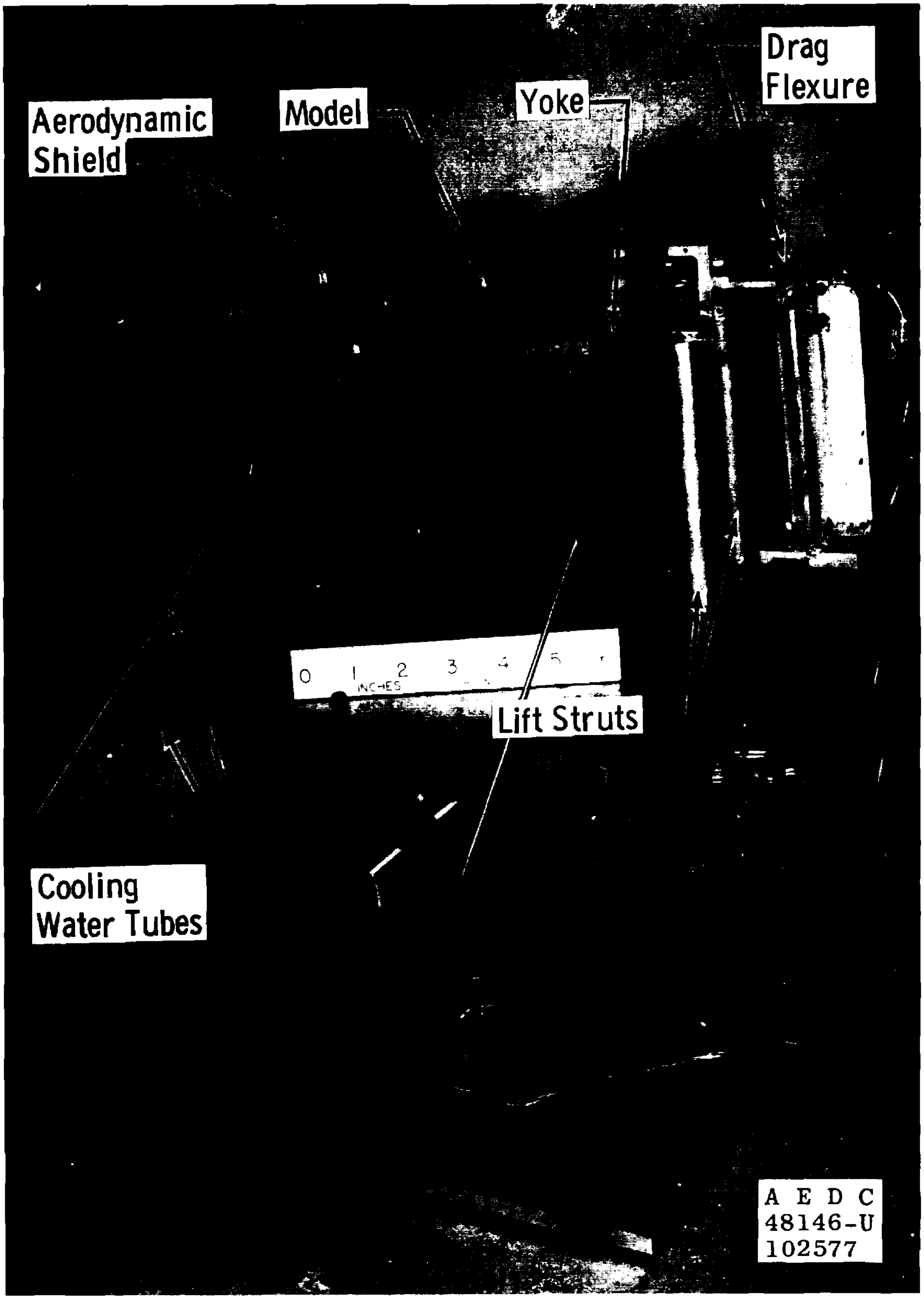


Fig. 3 Photograph of Balance

Moment Arm Schedule	
Station No.	x, in.
1	1.74
2	1.24
3	0.74
4	0.24
5	-0.26
6	-0.76
7	-1.26
8	-1.76

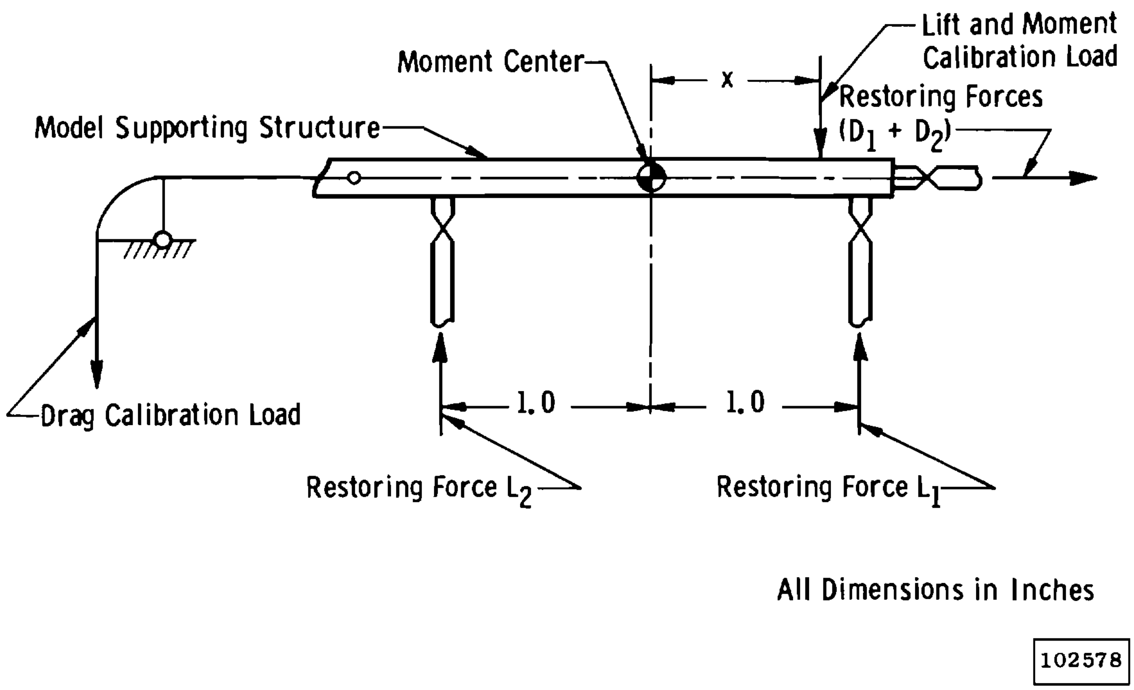


Fig. 4 Force Diagram of Balance and Calibration Loads

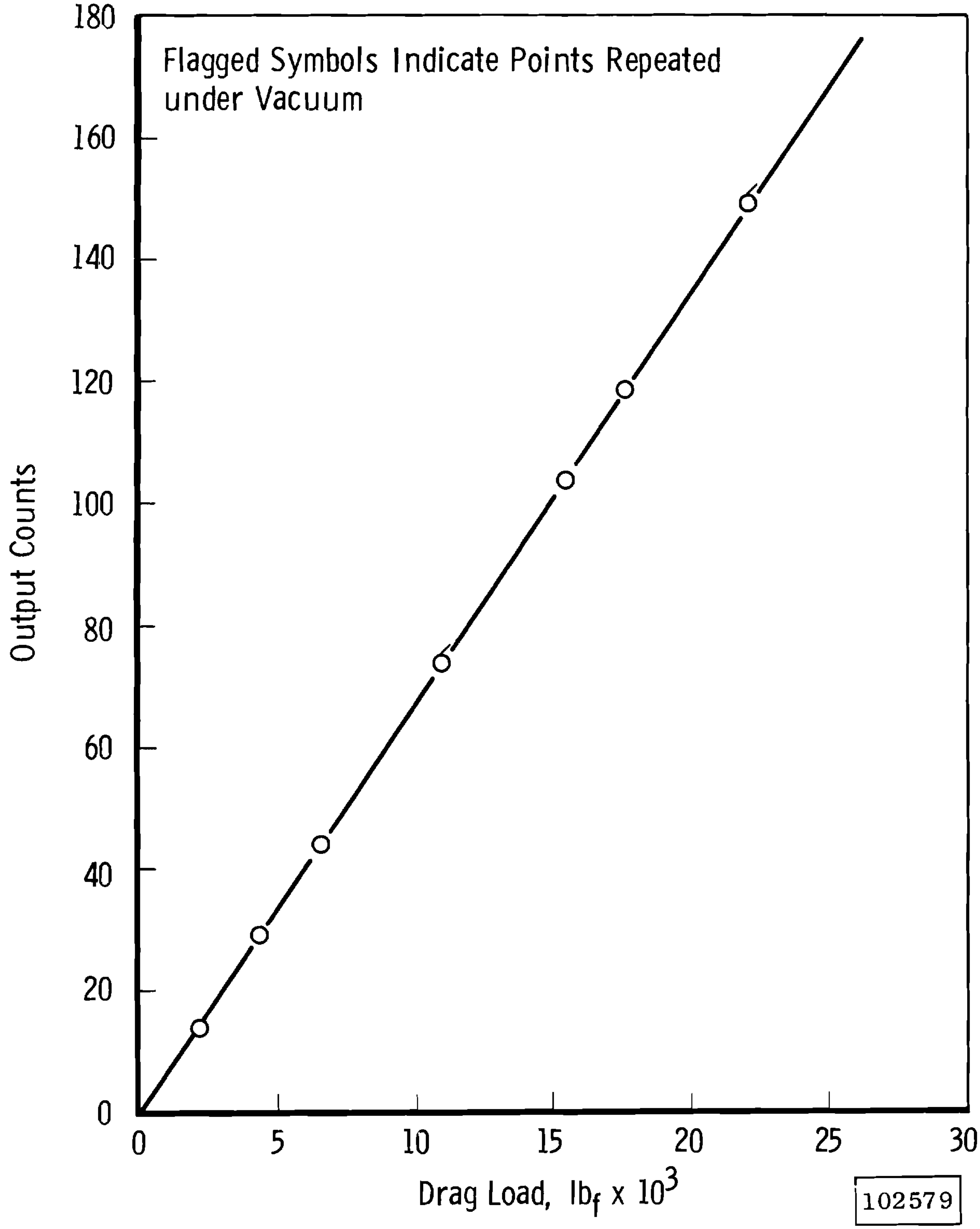
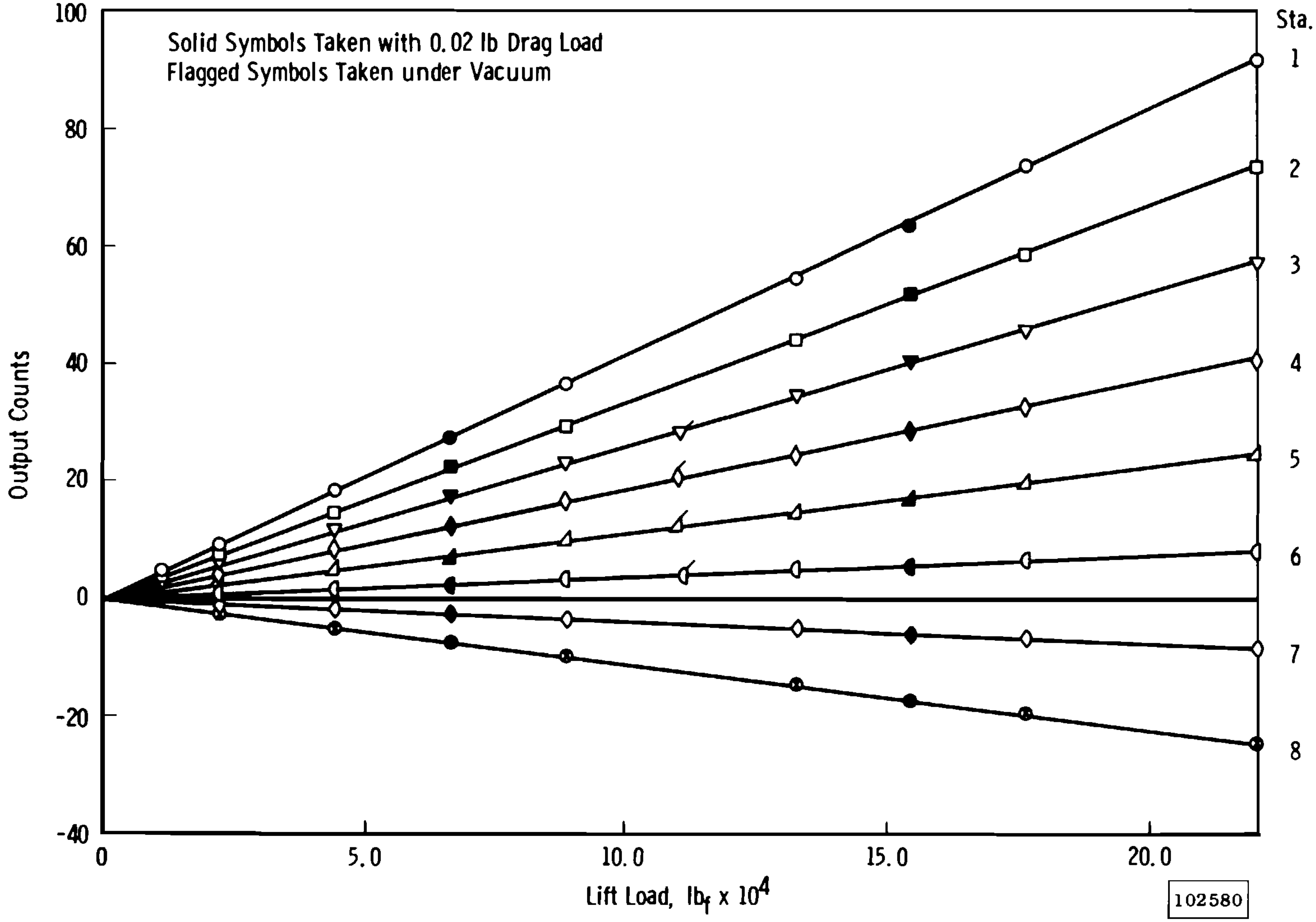
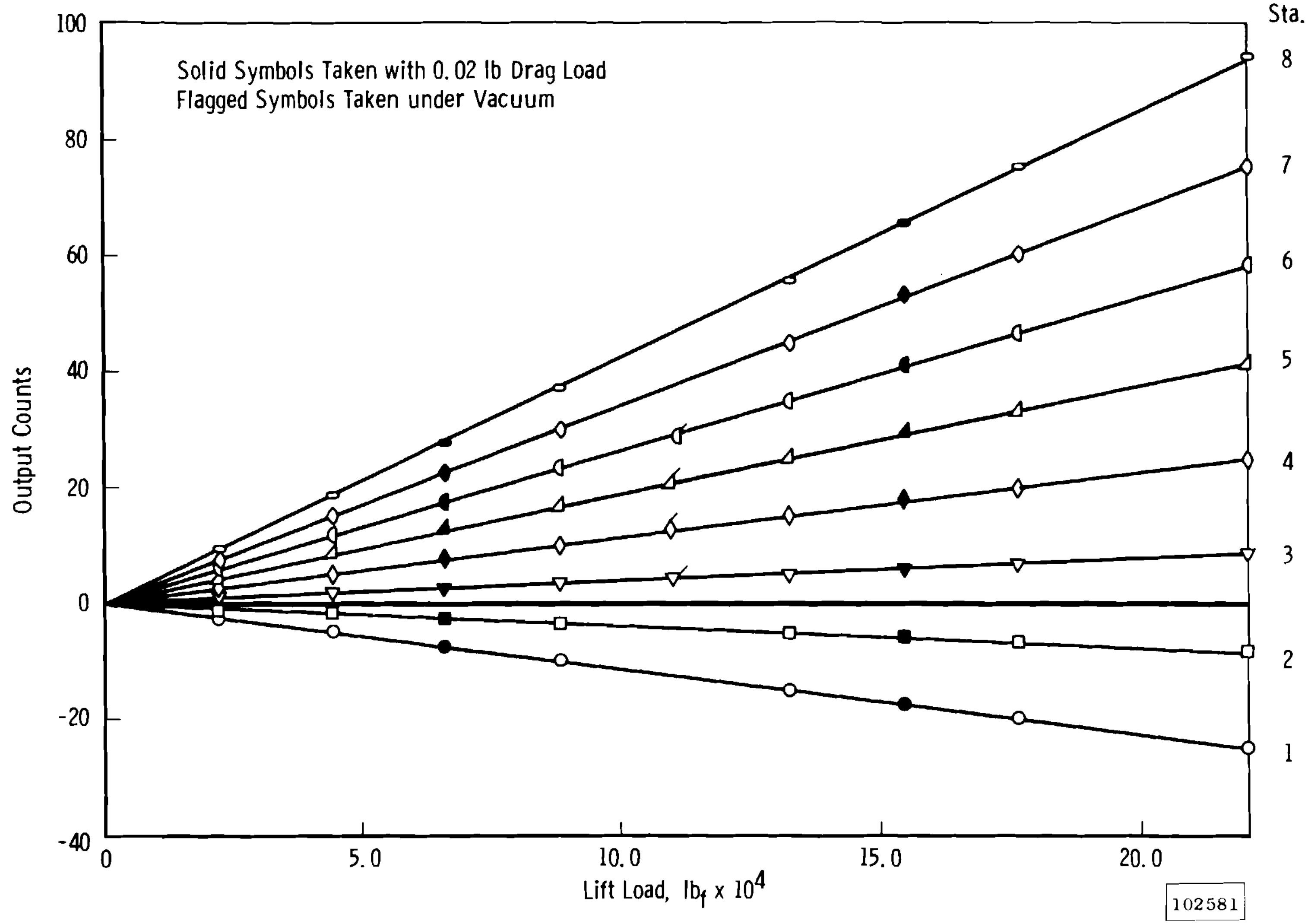


Fig. 5 Drag Output vs Load



a. Component L_1

Fig. 6 Lift Components Output vs Load



b. Component L_2

Fig. 6 Concluded

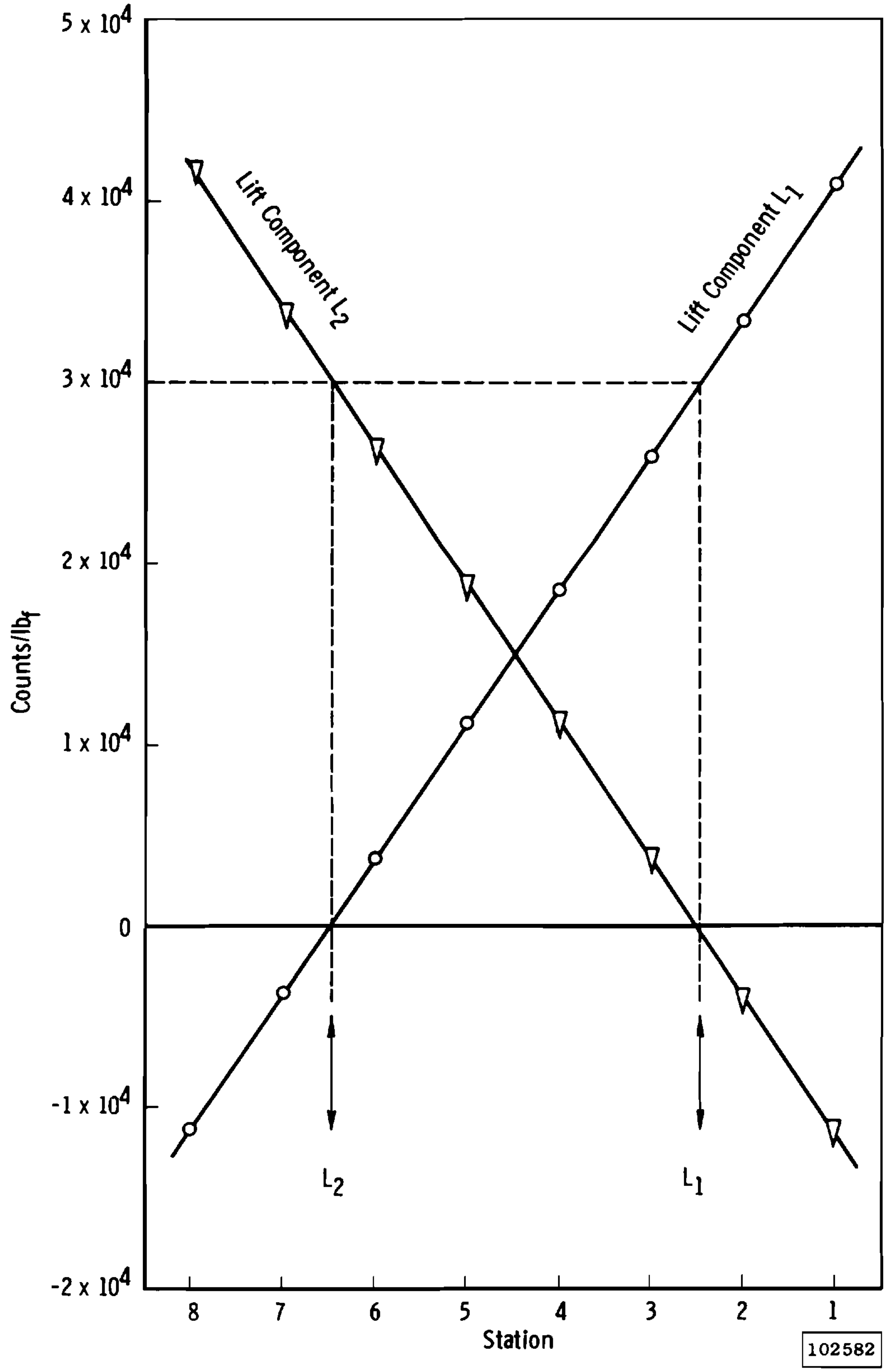


Fig. 7 Lift Components L_1 and L_2 Counts Output per Unit Load vs Station

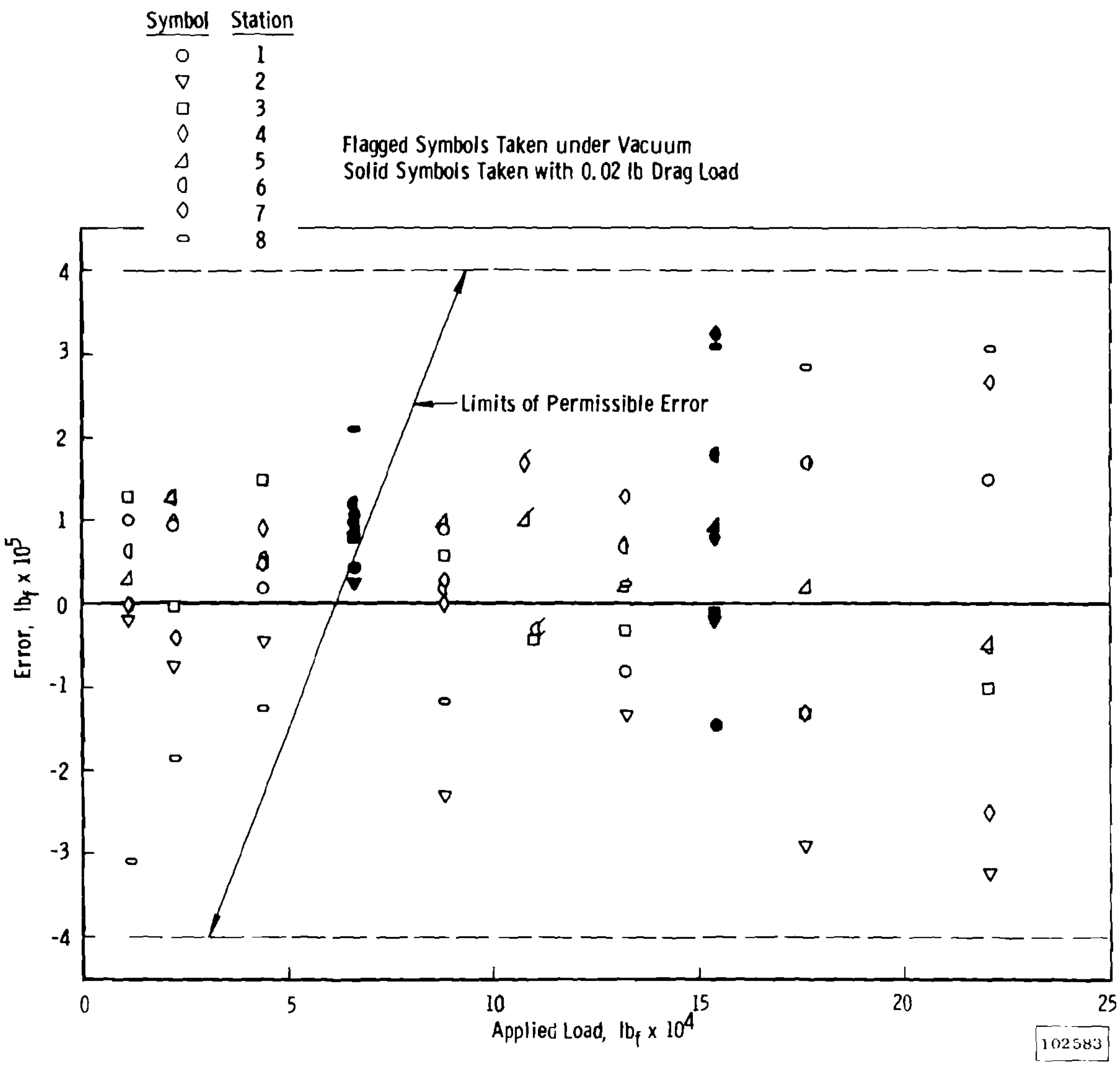


Fig. 8 Lift Load Measurement Error

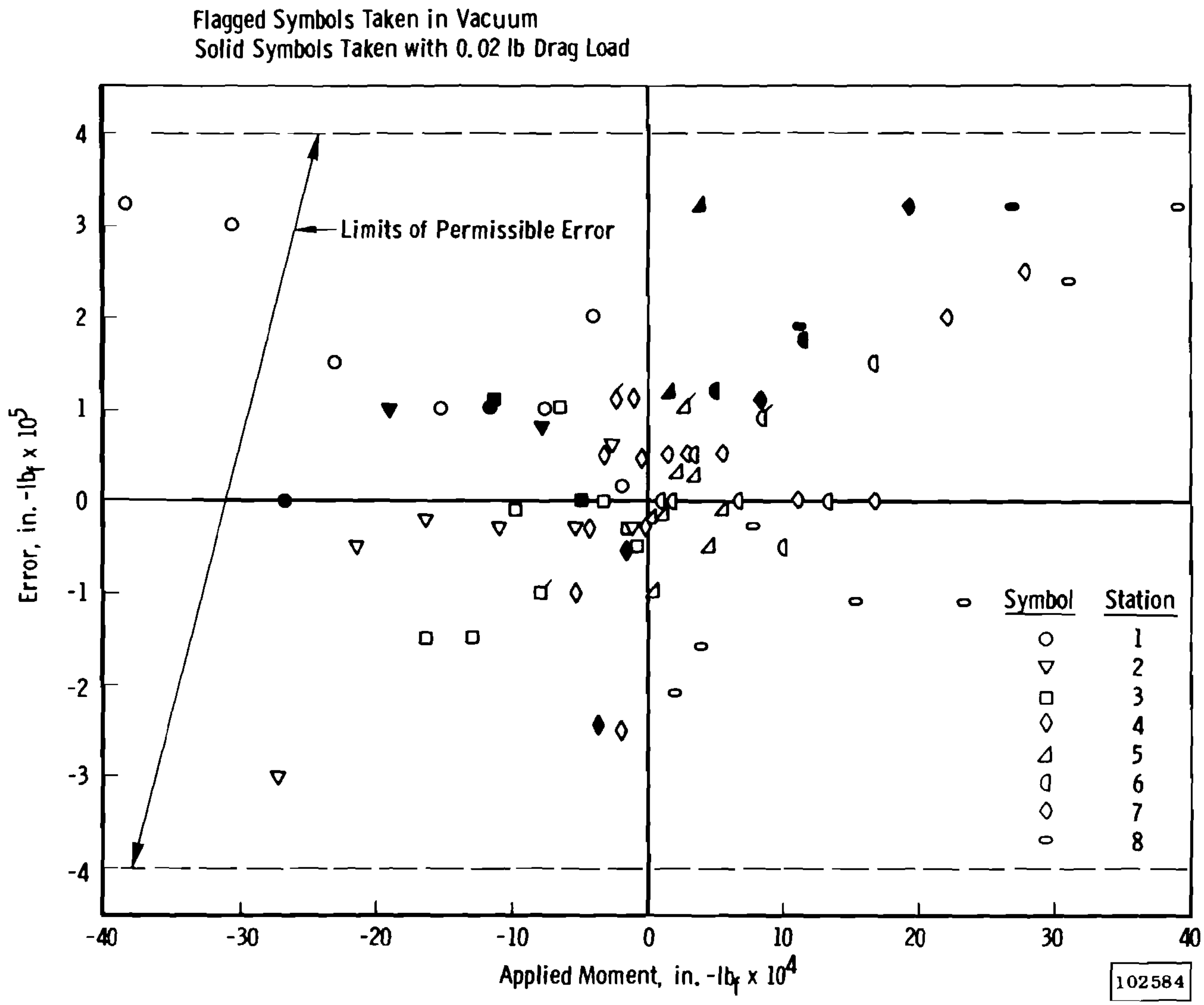


Fig. 9 Moment Measurement Error

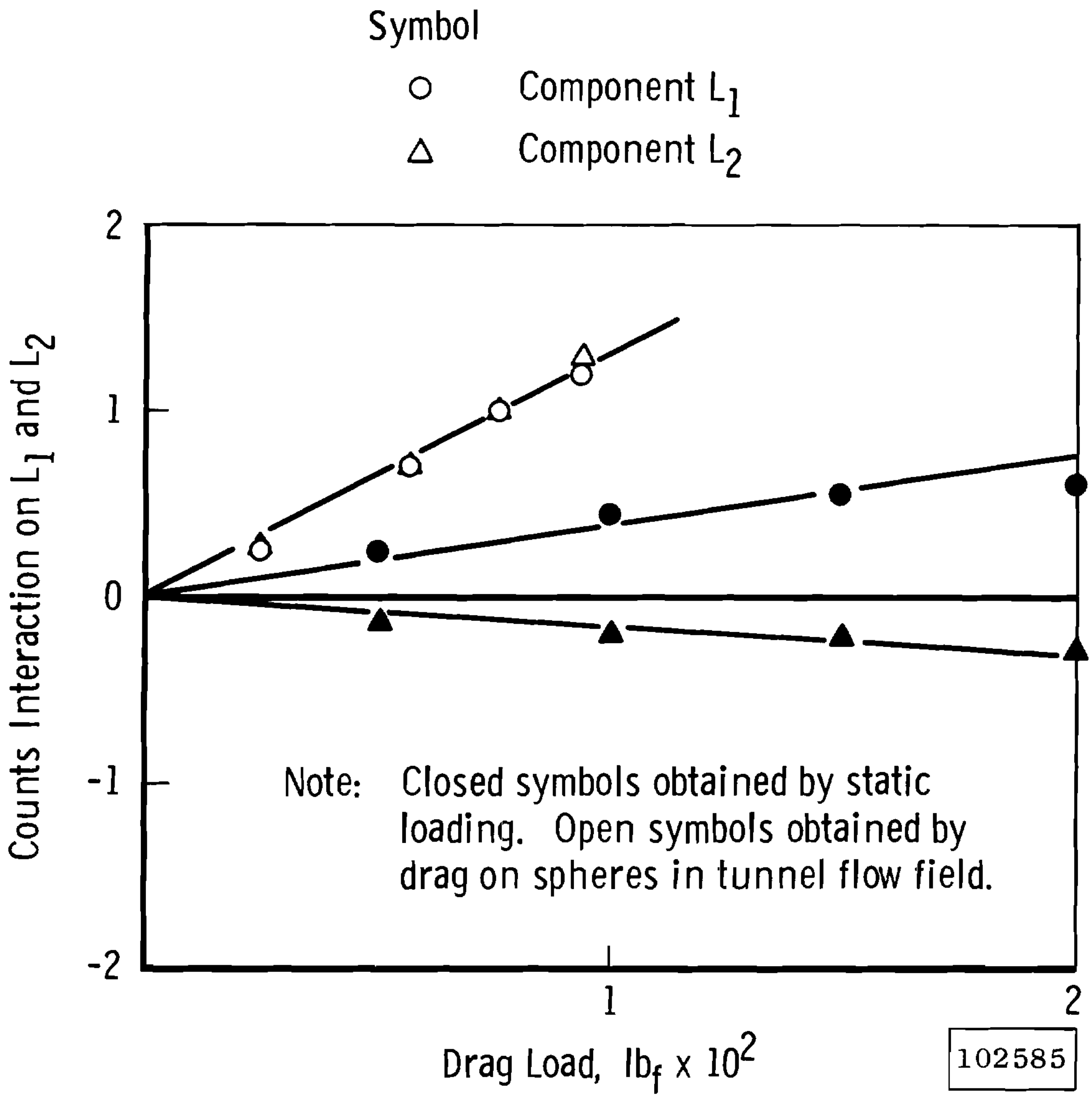


Fig. 10 Interaction of Drag Load on Lift Components

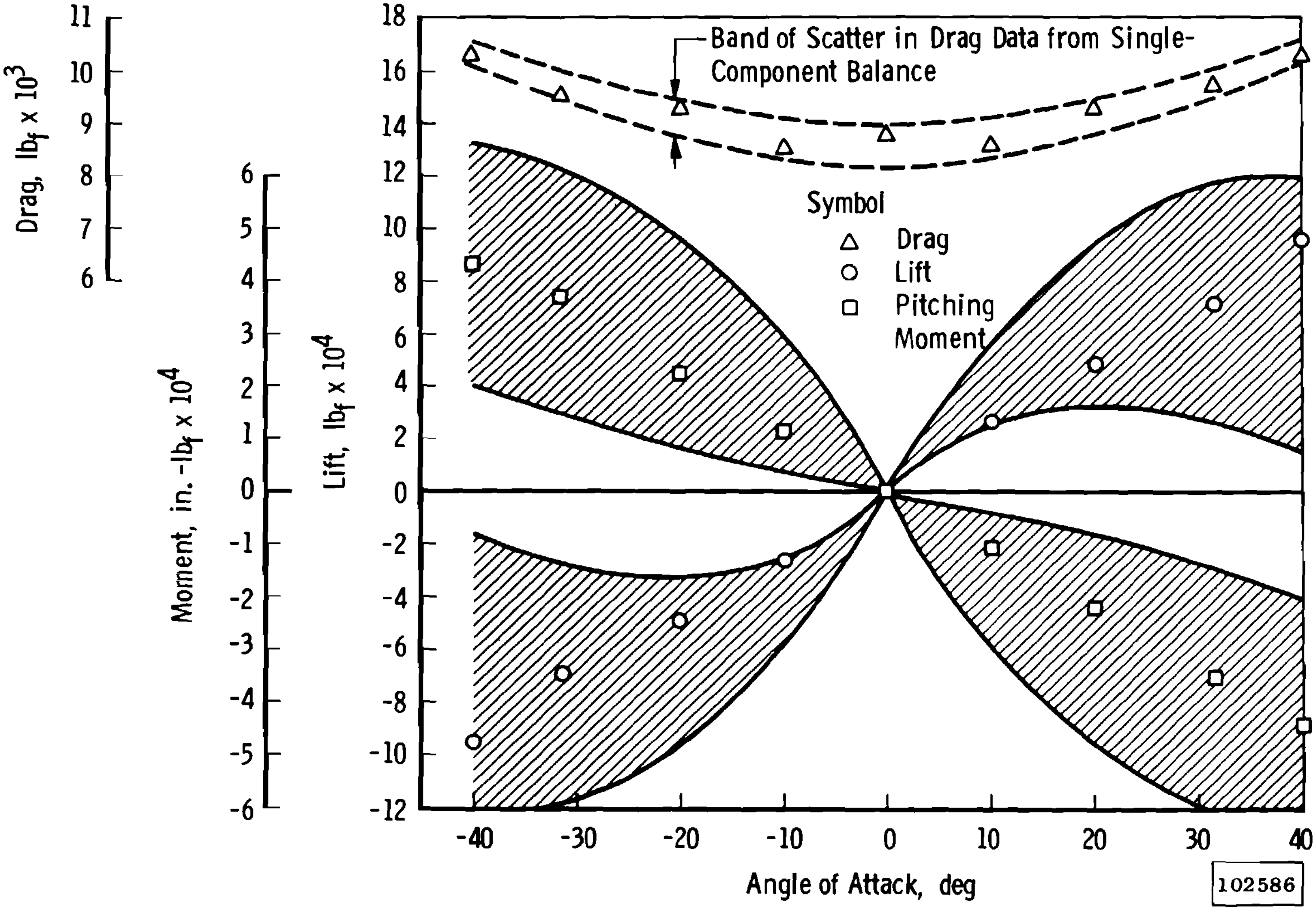


Fig. 11 Example Wind Tunnel Lift, Drag, and Pitching-Moment Measurements on Blunted Cone (Shaded Regions Lie between Extremes of Free-Molecular and Newtonian Theories for Lift and Moment)